

INVITED CLINICAL COMMENTARY

MANAGEMENT OF THE PATIENT WITH AN ACL/MCL INJURED KNEE

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ABSTRACT

The knee is a mobile functional anatomical unit which plays a key role in recreational function. In the last three decades, the knee has received a great deal of attention in the sports medicine literature, particularly in respect to isolated ligament pathology and management. In reference to combined multiple ligament pathology, a more limited number of articles exist, and indeed lead to confusing management. Although hundreds of publications address the topic of surgical correction of the anterior cruciate ligament (ACL), debate continues regarding clinical intervention for the patient with combined ACL and medial collateral ligament (MCL) management. Issues exist which the clinician must consider, including which structures require repair, timing of surgical intervention, and rehabilitation approaches. This article will attempt to define a treatment algorithm for the clinician to consider with simultaneous injury to the ACL and MCL.

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INTRODUCTION

The evolution of rehabilitation over the last 20 years has been to establish pathways with a foundation using evidence-based principles. However, if one uses the classic definition of evidence-based protocols with regards to the multiple ligament knee injury (MLKI), the results will be restricted when compared to the depth of structures such as the anterior cruciate ligament (ACL) or posterior cruciate ligament (PCL) in isolation.¹ Multiple authors²⁻⁵ have demonstrated results of non-operative intervention in the isolated medial collateral ligament (MCL) injury model. These studies have investigated parameters such as surgical correction, immobilization, and early functional rehabilitation in the patient with an isolated MCL injury. The reported outcome appears favorable, however, a small percentage of patients continue to demonstrate residual instability at four years post injury.² The model of both early motion and immobilization result in similar success with return to functional activity.² Lundberg et al³ reported a 74% return to normal knee function by three months post injury; 87% had return to normal function by four years; and by ten years only 13% demonstrated medial compartment osteoarthritic (OA) changes. Nonoperative and operative treatments of patients with MCL injuries lead to equally positive results. Additionally, MCL ruptures need not be treated operatively when the ACL is reconstructed in the early phase.⁴

The evolution of management of multiple ligament injuries to the knee received greater attention following O'Donoghue's⁵ 1970 description of the "Unhappy Triad Injury." He reported on the relationship of MCL, ACL, and medial meniscus injuries as they relate to sport specific functions. These injuries represent a complex mechanical pathology which initiated a debate over the correct surgical management in an era of sports medicine when both surgical and rehabilitation procedures were in their infancy. O'Donoghue⁵ was one of the first authors to discuss the effects of the valgus force at the knee from loading response through mid-stance, and the resultant strain to the injured MCL. He further described the anatomical relationship of the MCL to the medial meniscus and proposed gait demands as an indicator for treatment intervention.

Review of Injury Mechanism and Ligament Evaluation

Injuries to the knee follow a specific and well-defined pattern, resulting in high force production until tissue failure occurs. Multiple studies describe the key mechanism as an externally applied valgus force with the foot fixed at

the distal segment.^{5,6,7} The application of a valgus force at the knee results in ACL/MCL tears, lateral compartment bone bruise, and lateral meniscus tear. Grood et al⁸ described the primary restraint ligaments and secondary structures to function like cables on a bridge, with progressive force application causing an increase in the strain that is applied to the primary ligament, as well as the secondary stabilizers. At 20 degrees of knee flexion, the MCL is the primary stabilizer to the medial compartment, with the posterior medial capsule providing a critical secondary role.

The physical exam defines the extent of pathology to the medial ligament system and directs the clinician in the establishment of the initial phase of treatment. Evaluation of the medial compartment requires practiced skill of the clinician to control the direction of the evaluation forces and unwanted secondary motion. Avoiding tibial rotation while evaluating valgus rotation is critical to a reliable and valid evaluation technique. If external tibial rotation occurs with the evaluation, ensuing tension in the posterior medial corner will have a negative result on the evaluation. A bilateral comparison serves to provide a baseline for the clinician when testing the non-involved extremity first.

With a medial injury, three potential findings exist;

- Medial pain with no increase in translation = grade 1
- Medial pain with increased translation up to 5 mm = grade 2
- Medial pain with increased translation in excess of 10 mm = grade 3

If ACL or PCL pathology concurrently exists with the MCL pathology, valgus translation will be increased in the 0 degree position and in hyperextension. The related cruciate injury will be corroborated by a positive result with either the Lachman's test or appropriate PCL laxity test maneuver.

The authors suggest that a confirming magnetic resonance imaging (MRI) be performed to identify all possible internal joint derangements. This completes the loop and aids the clinician in the development of a comprehensive treatment program to include a conservative component and staging of the surgical procedure to assure higher success rate.

INITIAL TREATMENT ALGORITHM: THE CINCINNATI EXPERIENCE

Establishing a treatment pathway is based on a tiered approach with the dependent variables including but not

limited to ACL tear, degree of MCL tear, medial or lateral meniscus tear, chondral surface damage, and capsular injury. The period of time between injury and surgery also varies based on the severity of the injury and tissues involved. Control of the post-injury sequelae of range of motion (ROM), muscle control, allowance of time for scarring of the MCL, and protection of the region of the bone bruise will be factors in determining the time of surgical correction.

Grade 1 MCL – Injury with or without meniscus damage ACL surgery within one week; no pre-surgery motion restriction.

Grade 2 MCL – Injury with or without meniscus damage ACL surgery within two weeks; a seven day period of motion limitation (brace locked at 30 degrees but full motion preformed in rehabilitation on a daily basis, and after seven days the brace is unlocked to full motion).

Grade 3 MCL – Injury with or without meniscus damage ACL surgery at three weeks with a 10 day motion restriction period (brace locked at 30 degrees and full motion is preformed in rehabilitation starting day seven after injury, and brace unlocked after 14 days).

Among those patients with ACL/MCL injuries, two distinct groups exist, each with different prognoses related to return of motion based on the location of the MCL disruption. Patients with double-ligament injuries, where the MCL lesion is proximal, should be managed very aggressively to regain motion.⁹

The consequence of the bone bruise when present will result in restriction to weight bearing forces during this phase of the rehabilitation program. From the time of the initial injury until the completion of the post surgical rehabilitation phase, weight bearing is controlled. The post surgical weight bearing will be addressed in a later section. Likewise, meniscus involvement ranks higher in priority in reference to weight bearing, an MRI evaluation can identify the degree, position, and compartment of the meniscus tear, and may dictate weight-bearing progression with lateral meniscus requiring greater protection. The restriction for weight bearing post surgery would also be premised on the meniscus compartment and tear location.

NON-OPERATIVE TREATMENT

Currently, the standard of care for the patient with MLKI is surgical reconstruction of disrupted ligaments and repair

of the collateral ligaments when complete disruption of the fibers occurs. However, because of the complexity of the patient with MLKI, often concomitant neurological or vascular issues can arise delaying or preventing surgical intervention all together. Wascher et al¹⁰ cited a 10% incidence of life-threatening chest, abdominal, and head injuries in the patient with MLKI.¹⁰ In addition, other musculoskeletal issues can occur to the surrounding hip, femur, and tibia. Of particular concern, is the popliteal artery and peroneal nerve, which can be easily affected with varus force at time of injury. Both structures need to be assessed at time of injury to ensure immediate care.

Because of these issues and the fact that every patient should be treated on an individual basis, select times exist when surgery on these patients is not performed. In these cases, the definitive treatment is not well-defined. Treatments for this population range from extended immobilization and external fixators for complete dislocations to immediate motion, preferring laxity to scarring of tissue. The decision making process is highly dependent on the degree of injury, patient type, and surgeon's preference. In a young and athletic population, however, surgical correction is almost always recommended.

POST-OPERATIVE REHABILITATION

PHASE I: Program Objectives

The key is to identify the rehabilitation components that the therapist must address in order to restore normal function, and then progressing the exercise program to higher levels of function until the patient achieves an optimal level of function. The therapist considers a staged approach, and must assess the interaction of how one component is influenced by another. The components of the program include:

- Regulate post-surgical pain to avoid influence on ROM and muscle contraction.
- Reduce post-surgical hemarthrosis to avoid muscle shutdown and arthrofibrosis.
- Re-establish joint ROM as the primary objective in order to avoid deleterious motion loss.
- Advance weight bearing and development of normal gait mechanics without affecting the biological graft.
- Establish early exercise sequences to recondition the muscular system while minimizing risk to biological graft.
- Re-train the mechanoreceptor system through proprioception program.

- Establish subjective and objective data to identify deviations from norm to minimize influence on the outcome.
- Establish a functional algorithm to verify functional progression.
- Progressive functional return to activity and sport.

In addition, outcome success is dependent on the understanding that patients have intrinsic and extrinsic variable factors that influence the level of activity to which they return. Intrinsic factors may include, but not be limited to, tissue type, muscle type, potential for excessive scar formation, general medical well being, osseous alignment, lower extremity mechanics, and compliance to program. Extrinsic variables include, but may not be limited to, social habits, use of nicotine products, environmental situations, and economical reality. Rehabilitation requires the therapist to address many of these issues.^{1,11}

Re-establishing Range of Motion

The first goal in the rehabilitation program is obtaining full ROM. The use of continuous passive motion (CPM) after surgical procedures arose from a combination of animal and human studies in the late 70's and early 80's.¹²⁻¹⁵ The primary focus of these studies was to assess forces applied by early motion on the biological graft and surrounding tissues. This was a 180 degree shift in post surgical management. The rationale for the changing philosophy was the morbidity of the joint associated with prolonged immobilization. Early studies were undertaken to determine if early use of CPM would provide a positive influence on graft re-vascularization and collagen regeneration, but findings demonstrated no cause and effect relationship. The positive findings identified with these studies included earlier redevelopment of ROM, decreased post surgical pain, decreased joint hemarthrosis, decreased scar tissue, and maintaining viability of the articular cartilage in the joint.

Currently, the recommendation for the use of a CPM machine immediately post surgery is 10 to 12 hours/day until the unit is at maximum range. Most patients are able to tolerate a gradual increase in motion, discontinuing the unit after seven to 10 days. On average, the patients adjust their motion 10 to 15 degrees a day. If CPM is not desired, self-ranging exercise can be preformed utilizing the contralateral extremity on an hourly basis.

Weight Bearing

The second goal in the early rehabilitation period is the progression of the weight bearing process. Again, a range

of weight bearing progression exists in current protocols, some of which advocate immediate full weight-bearing in a locked extension brace, while others advocate the use of crutches for upwards of four to five weeks. The concept of immediate full weight bearing programs has prevailed with the thought that the weight bearing facilitates faster extensor mechanism return. No data appears to support this claim and the patient may accommodate for a poor extensor mechanism by ambulating in a leg vault gait pattern.^{16,17} Allowing an asymmetrical gait pattern secondary to extensor mechanism weakness leads to the potential development of a recurvatum at the midstance position. This recurvatum may result in an unwarranted side-effect of a prolonged altered gait pattern at midstance, due to poor extensor eccentric control as the knee attempts to go into flexion of 15 to 20 degrees. Our approach has evolved to allow immediate partial weight bearing in either a protective ROM device or no brace at all. From the initial phase, gait mechanics are retrained without compensation beginning on the first day. Concurrently, the patient is placed in a gait training program to emphasis the proper position and strength. To progress the weight bearing program, the clinician must assess the factors that influence the gait pattern and the biological graft:

- Motion must progress as weight bearing is advanced.
- Extensor strength is able to control 0 degrees ROM without extensor lag.
- Joint effusion is resolving as demonstrated by objective measures.
- Joint arthrometer evaluation is not significantly changed on a test retest basis.
- Pain control has been achieved to avoid sympathetic maintained pain patterns.

A post-surgical knee orthosis is fitted at the time of surgery to allow for early weight bearing with crutch support. The brace is unlocked to allow for normal gait mechanics and avoidance of deviations commonly seen with patients in a locked brace. These deviations include a vaulting gait, circumduction of the involved lower extremity, or avoidance of weight bearing on the limb.

Muscle Re-education

Re-establishing muscle control after joint surgery over the last 20 years has changed dramatically and has many different pathways. This process of re-establishing muscle control is initiated immediately, compared to 30 years ago when the patient was casted for six weeks or longer. The evolution has been brought about by basic scientific stud-

ies allowing a better understanding of joint compression forces, exercises forces applied to the ligament, improved surgical techniques, and avoiding joint morbidity effects.

Initially, the goal is to simply retard the effects that joint hemarthrosis and surgical pain have on the muscle by causing reflex shutdown. The classic use of isometrics, open chain isotonic such as active range of motion with the weight of the ankle, and straight leg raises can be beneficial. These exercises are generally low load and independently may not prevent the disuse muscle atrophy that affects the knee joint.

Over the years many exercise approaches have been advocated and in some cases are associated with several complications. Although the trend is to accelerate patients, patellar tendonitis is common with a 9% occurrence rate.¹⁷ Of greater concern is the development of patello-femoral arthritis, which has been reported in a 7% to 51% range in association with ACL reconstructions.¹⁷ Early phase extensor mechanism exercises may generate large forces across the articular surfaces of the patella. Rehabilitation, therefore, must not only account for the healing graft, but also patella protection. Patellar degeneration is unpredictable and varies among patients especially with reference to age range. Shino et al¹⁸ reported that on second look arthroscopy 51% of allograft patients demonstrated patellar changes, yet only 17% of the patients reported subjective complaints. Autograft studies describe subjective complaints ranging from 7% to 29%.^{11,19,20} Another associated complication leading to patella complaints is infra-patellar contracture syndrome, described as a distal migration of the patella secondary to scaring in the fat pad, or a shortening of the patellar tendon, which can occur after surgery.²¹ In this scenario, the patella is displaced onto the trochlear surface, consequently increasing patellar compression and shear load. Maintaining adequate extensor mechanism control in the zero degree position can help avoid these complications. In addition, emphasizing early patellar mobilization immediately following surgery can help to prevent infra-patellar contracture later in the rehabilitation process.

In order to both understand the process of neurologically induced muscle shutdown and to develop rational treatment approaches, the therapist must understand the reflex inhibitory mechanism. The key to this process is historical and well defined. Newton²² identified four neural components to the mechanoreceptor system; these either inhibit or facilitate muscular response to input. Kennedy et al²³

demonstrated the influence of joint pressure on mechanoreceptors as inhibitors resulting in extensor mechanism shutdown; however, this study did not quantify muscle loss percentages. In 1984, the senior author described how a mere 70 cc's of injected saline reduced isometric output of the knee by 37% in a normal joint.²⁴

In the last 15 years the use of muscle stimulation has gained wider acceptance and is now considered part of standard care.^{11,25,26} Attempting to achieve two objectives, the rehabilitation program utilizes electrical currents in an attempt to reduce the influence of pain as well as re-establish muscle control of joint motion. Immediately following injury, the use of a stimulation unit to modulate pain helps to provide control of a patient's subjective complaints. This control is achieved using TENS type stimulation, such as an Empi 300PV system (Empi, St. Paul, MN) utilized on a 24 hour a day basis. Secondly, the Empi 300 PV is programmed so that voluntary muscle control of the extensor mechanism is facilitated with the assistance of muscle stimulation applied to the vastus medialis oblique muscle region and the proximal location of the femoral nerve. The goal of this program is to augment and produce a stronger contraction of the extensor mechanism. As a patient's program progresses and the extensor mechanism becomes able to achieve a 0 degree position, the patient is moved to more closed chain functional positions to replicate challenges of maintaining the knee in ideal positions for activities of daily living and sports.

PHASE II: Program Objectives

Typically during the six to 12 week time period, patients graduate to advanced neuromuscular and functional training.^{16,27,28} At this time, exercise intensity is increased to allow for the muscle adaptation, a requisite for sport-specific demands. Areas of importance and emphasis during this time period are muscle strength, power, endurance, and control. Aspects of acceleration, deceleration, and reflex response are slowly integrated into the rehabilitation program. The progression of training should increase the duration of the exercise session first, then increase the intensity of the workload, and finally integrate functional training with sport specific drills.

Muscle Re-Education

During rehabilitation, emphasis should be placed on training the entire kinetic chain, not just the involved lower extremity. Proximal stabilization is of particular importance to the athlete and should be incorporated from the early postoperative phase until return to sport. The hips,

pelvis, lumbar spine, and abdominal musculature are areas of primary focus. Straight leg raises are initiated early and progress to higher resistance, providing early stage training but limited functional carry over. In essence, these exercises are isometric to the vasti group; the long lever arm minimizes the total amount of resistance.

To initiate training for rapid response time of the muscles that are required to control tibial translation involves incorporating high-speed training of the proximal stabilizers of the hip and pelvis. This proximal strategy is part of the core stabilization program. Core muscle group training includes bridges using bilateral lower extremities, which progress to bridges with single limb support and alternate leg extension. Single leg bridges are held for 10 seconds at a time. Single leg bridges are a more advanced core stability exercise and should be performed for both involved and uninvolved extremities. At this point, side-lying bridges should also have been implemented, advancing by abducting the contra-lateral arm and using weights to increase the balance component. It is important to continuously reinforce proper lumbo-pelvic positioning while avoiding faulty patterns. Abdominal and oblique muscle exercise advancement is paramount during this phase of rehabilitation. Dynamic rotation, plyometric sit-ups, and power training are progressed at this time. All of these exercises can be performed in supine, standing, and in sport and position-specific athletic positions, all of which emphasize total body control and stabilization.

Open kinetic chain knee exercises are continued during this phase. Both isotonic workloads and isokinetic training sessions are helpful. Care must be taken to protect the healing graft and to avoid patellofemoral joint irritation. Isotonic extension work should be limited to arc of 90-30 degrees, and heavy resistance loads should be avoided. Hamstring workload is not limited, unless a posterolateral capsule or meniscal involvement exist. The senior author has advocated an approach utilizing higher velocity for evaluation and training to protect the patella and graft.^{27,28} In closed chain training 0 degree stops are used to prevent knee hyperextension. Markolf et al²⁹ reported that hyperextension ROM placed the highest forces on the ACL.²⁹

Closed kinetic chain training also plays a primary role in ACL rehabilitation. This rationale is based on the performance of functional training and strengthening simulating both sport specific movement and those associated with activities of daily living. The literature supports this training based on data from both cadaveric and in vivo models.

Both Beynnon et al³⁰ (performing in vivo measurement) and Wilk et al³¹ (by mechanical methods) predicted low strain on the ACL in the closed chain position. They also reported that the quadriceps and hamstrings muscles co-contract to protect the ACL graft against strain.^{30,31} Others also report that the closed chain position allows exercises for early resistance training to the lower extremity.³²

Particular emphasis should be placed on single leg training to enhance neuromuscular control of the knee. Focus on postural awareness and postural stability in the single limb supported position is paramount for an athlete to return to competition. Athletes in competition spend a critical amount of time in the single leg position, executing movements such as running, cutting, pivoting, jumping as well as various acceleration and deceleration maneuvers. As part of the rehabilitation continuum to successfully return an athlete to their prior competitive level, training and assessment of proper landing mechanics is performed early in the program. In patients with weak proximal joint segments, valgus (at the knee) and internal rotation (at the hip) increase the strain on the ACL. Landing training begins with the eccentric step down program and builds to dynamic and responsive stability in the single leg exercise position.³³

Training in the single leg position is progressed from a very controlled environment, focusing on balance in addition to posture and control of the entire kinetic chain. Dynamic stability is gradually introduced by altering the base of support, involving the upper extremities, incorporating sport specific activities, and lastly implementing rotational components to the program. Kicking exercises with resistive bands at high speeds can be performed at the five to six week time period as a rhythmic stabilization drill. Lunging exercises are progressed by means of altering surfaces, providing manual perturbations, and eventually, performing sport specific tasks. Single limb training promotes stabilization of the entire lower extremity and should be performed concurrently with the hip/pelvis/trunk stabilization program previously described. The athlete must learn to control the body as it transitions from one point to the next, including forward, backward, and lateral movements.

Between weeks six and 12, overall strengthening and stabilization of the lower extremity continues; however, speed of performance is also progressively emphasized. Many exercise variations exist that can be implemented early that slowly progress toward higher speed maneuvers.

Elastic bands, lunges, and many stepping and footwork drills can progress toward higher speeds. Over time, repetitions and durations of exercise should increase; ensuring a combination of both submaximal and aerobic training. The critical element at this time period is endurance activity to counterbalance muscle fatigue.

PHASE III: Return to Activity

Return to activity, on the average, is a bell shaped curve. The range of return is 12 weeks for the hypo-elastic patient and up to 12 months for the hyper-elastic patient. On average, six months serves as our mean time for a safe return to activity, based on biological healing of the graft. For return to activity the following objective and subjective evaluation should occur:

- 1: Subjective rating on the International Knee Documentation Committee (IKDC) scoring system³⁴ as compared to pre-injury status
- 2: Joint arthrometer score of 3 mm or less (patients above this parameter may be held longer)³⁵
- 3: Objective muscle scoring within 85% of the contralateral extremity³⁶
- 4: Functional hop scores within 85% of the contralateral extremity^{37,38}
- 5: Progressive drill re-enactment to simulate activity anticipated upon return to sports
- 6: Confidence by patient to psychologically perform skill specific activity

CONCLUSION

Management of the patient with injury to both the ACL and the MCL can become complicated and confusing. As a number of knee injuries do involve multiple ligaments, especially in sports, it is important to use a well thought out program for rehabilitation. Focus should be placed on both ligaments, so that rehabilitation of one does not detrimentally affect rehabilitation of the other. This manuscript presented a treatment approach using an algorithm which includes focusing on increasing range of motion, developing normal gait mechanics, reconditioning the muscular system, and progressing functional return to activity and sport.

REFERENCES

1. Noyes FR, DeMaio M, Mangine RE. Evaluation based protocols: A new approach to rehabilitation. *J Orthop.* 1991; 14:1383-1385.
2. Reider B, Sathy MR, Talkington J, et al. Treatment of isolated medial collateral ligament injuries in athletes with early functional rehabilitation. *Am J Sports Med.* 1994; 22:470-477.
3. Lundberg M, Messner K. Long-term prognosis of isolated partial medial collateral ligament ruptures. *Am J Sports Med.* 1996; 24:160-163.
4. Halinen J, Hirvensalo E, Santavirta S. Operative and nonoperative treatments of medial collateral ligament rupture with early anterior cruciate ligament reconstruction. *Am J Sports Med.* 2006;34:1134-1140.
5. O'Donoghue A. *Treatment of Injuries to Athletes.* Philadelphia, PA: WB Saunders Company. 1970.
6. Indelicato PA. Isolated medial collateral ligament injuries in the knee. *J Am Acad Ortho Surg.* 1995; 3:9-14.
7. Ford KR, Myer GD, Hewett TE. Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc.* 2003; 35: 1745-1750.
8. Grood ES, Suntay WJ, Noyes FR, Butler DL. Biomechanics of the knee-extension exercise. *J Bone Joint Surg.* 1984;66: 725-733.
9. Robins AJ, Newman AP, Burks RT. Postoperative return of motion in anterior cruciate ligament and medial collateral ligament injuries. The effect of medial collateral ligament rupture location. *Am J Sports Med.* 1993; 21: 20-25.
10. Wascher DC, Dvirnak PC, DeCoster TA. Knee dislocation: Initial assessment and implications for treatment. *J Orthop Trauma.* 1997;11: 525-529.
11. DeMaio M, Noyes FR, Mangine RE. Principles for aggressive rehabilitation after reconstruction of the anterior cruciate ligament. *J Orthop.* 1992;15:505-515.
12. Burks R, Daniel D, Losse G. The effect of continuous passive motion on anterior cruciate ligament reconstruction stability. *Am J Sports Med.* 1984;12:323-326.
13. Drez D, Paine RM, Neuschwander DC, Young JC. In-vivo measurement of anterior tibial translation using continuous passive motion. *Am J Sports Med.* 1991;19:381-383.
14. Noyes FR, Mangine RE, Barber SD. Early knee motion after open and arthroscopic anterior cruciate ligament reconstruction. *Am J Sports Med.* 1984;15: 149-160.
15. Salter RB. The biologic concept of continuous passive motion on synovial joints. *Clin Orthop.* 1989;242:12-25.
16. Shelbourne KD, Nitz P. Accelerated rehabilitation after anterior cruciate ligament reconstruction. *Am J Sports Med.* 1990;18:292-299.
17. Noyes FR, Mangine RE, Barber. The early treatment of motion complications following reconstruction of the anterior cruciate ligament. *Clin Ortho.* 1992; 220:275-283.
18. Shino K, Inouse M, Horibe S, et al. Maturation of allograft tendons transplanted into the knee. An arthroscopic and histological study. *J Bone Joint Surg.* 1988;70:103-121.
19. Benyon BD, Johnson RJ, Fleming BC, et al. Anterior cruciate ligament replacement: Comparison of bone-patellar tendon-bone grafts with two strand hamstring grafts. *J Bone Joint Surg.* 2002;84:1503-1513

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20. Noyes FR, Barber SD, Mangine RE. Bone-patellar ligament-bone and fascia lata allografts for reconstruction of the anterior cruciate ligament. *J Bone Joint Surg.* 1990; 71: 1125-1132.
 21. Tambrello MT, Personius WJ, Lamb RL, et al. Patella hypomobility as a cause of extensor lag. Presented at Total Care of the Knee: Before and After Injury. Cybex Conference, Overland Park, KS, May 17-19 1985.
 22. Newton RA. Joint receptor contribution to reflexive and kinesthetic responses. *Phys Ther.* 1982; 2: 22-29.
 23. Kennedy JC, Alexander IJ, Hayes KL. Nerve supply of the human knee and its functional importance. *Am J Sports Med.* 1982; 10: 329-335.
 24. Mangine RE, Brownstein B. Effects of joint effusion on muscle performance. Abstract in Cybex proceedings manual, education conference, Kansas City, MO, May 1984.
 25. Minning SJ, Myer GD, Mangine RE, et al. Serial assessments to determine normalization of gait following ACL reconstruction. *Scand J Med Sci Sports.* 2008, E-pub ahead of print.
 26. Snyder-Mackler L, Delitto A, Bailey SL, Stralka SW. Strength of the quadriceps femoris muscle and functional recovery after reconstruction of the anterior cruciate ligament: A prospective, randomized clinical trial of electrical stimulation. *J Bone Joint Surg.* 1995;77: 1166-1173.
 27. DeMaio M, Mangine RE, Noyes FR, Barber SD. Advanced muscle training after ACL reconstruction: Weeks 5 to 52. *Orthopaedics.* 1992; 15: 757-767.
 28. Mangine RE, Heckmann TP, Eldridge VL. Muscle response to strength training. In, Scully RM, Barnes MR eds. *Physical Therapy.* Philadelphia, PA, JB Lippincott Co. 1989: 739-762
 29. Markolf KL, Gorek JF, Kabo M, Shapiro MS. Direct measurement of resultant forces in the anterior cruciate ligament. 1990; *J Bone Joint Surg.* 72: 557-562.
 30. Beynnon BD, Fleming BC, Johnson RL, et al. Anterior cruciate ligament strain behavior during rehabilitation exercises in vivo. *Am J Sports Med.* 1995;23: 24-34.
 31. Wilk KE, Escamilla RF, Flesig GS, et al. A comparison of tibiofemoral joint forces and electromyographic activity during open and closed kinetic chain exercises. *Am J Sports Med.* 1996;24:518-527.
 32. Jenkins WL, Munns SW, Jayaraman G, Werzberger KL. A measurement of anterior tibial displacement in the closed and open kinetic chain. *J Orthop Sports Phys Ther.* 1997; 25:49-56.
 33. Hewett TE, Paterno MV, Meyer GD. Strategies for enhancing proprioception and neuromuscular control of the knee. *Clin Orthop.* 2002;402:76-94.
 34. Irrgang JJ, Anderson AF, Boland AL, et al. Development and validation of the international knee documentation committee subjective knee form. *Am J Sports Med.* 2001; 29:600-612.
 35. Daniel DM, Malcom LL, Stone ML, et al. Quantification of knee stability and function. *Contemporary Orthop.* 1982; 5:83-91.
 36. Wilk KE, Johnson RD, Levine B. Reliability of the Biodex B-2000 isokinetic dynamometer. *Phys Ther.* 1988; 68: (abstract), 220.
 37. Noyes FR, Barber SD, Mangine RE. Abnormal lower limb symmetry determined by function hop tests after anterior cruciate ligament rupture. *Am J Sports Med.* 1991;19: 513-518.
 38. Tegner Y, Lysholm J, Lysholm M, Gillquist JA. Performance test to monitor rehabilitation and evaluate anterior cruciate ligament injuries: *Am J Sports Med.* 1986; 14: 156-159.